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CHARGE-2B ELECTRON GUN SYSTEM

Utah State University

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An extremely versatile, modulated electron gun (MEG) system has been designed, fabricated and tested. The Herrmannsfeldt electron optics computer simulation code was used to great advantage during the design. The code was subsequently validated to high accuracy during hardware testing. A ground fault interruptable high voltage battery stack has been developed, which will greatly enhance system reliability during flight. MEG laboratory performance test results are discussed, along with the performance diagnostics to be flown together with the MEG on the upcoming CHARGE-2B sounding rocket mission.

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CHARGE-2B ELECTRON GUN SYSTEM FINAL REPORT

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Introduction

The prime objective of the CHARGE-2B sounding rocket experiment is to measure VLF waves generated by a pulsing electron beam. It has been proposed that a pulsed electron beam in the ionosphere will function as an antenna and generate electromagnetic waves which will propagate to the Earth's surface. It is the intent of the CHARGE-2B experiment to pulse an electron beam in the ionosphere and measure the resultant VLF waves both at deployed payloads in the ionosphere and at the ground. This report will document the progress on the CHARGE-2B electron gun and associated diagnostics.

The Modulated Electron Gun (MEG) for the CHARGE-2B experiment is the next generation of the Fast Pulse Electron Gun (FPEG) developed for the CHARGE and CHARGE-2 experiments. The MEG has been developed at Utah State University by the Space Dynamics Laboratory (SDL). Each MEG will operate at an accelerating potential of 3 kV with a maximum beam current of approximately 1 A. Three MEG modules will be flown to provide a total beam emission of 3 A. The design of the electron gun incorporates the use of a modulator circuit since the electron gun must be pulsed in the VLF range, which requires switching 3 kV with speed and accuracy. The objective in designing the MEG was to allow for a wide variety of selectable pulsing frequencies and programmable waveforms in order to maximize the flexibility of the electron gun. Thus a waveform generator circuit is required to produce the desired waveform for the pulsing electron beam. A sinusoidal variation of beam current has been chosen for the CHARGE-2B experiment. This choice was made to maximize the power in the fundamental emission frequency since fewer harmonics are produced by a sinusoidal variation.

The electron gun must therefore consist of a power supply, a waveform generator, a modulator, and the gun optics (cathode and anode). In addition to this, a beam current monitor has been incorporated into the design of the MEG. A Rogowski coil is used to monitor the emitted beam current. The Rogowski coil is mounted at the exit port of the gun optics, surrounding the aperture through which the electrons are accelerated, allowing a measurement of the current that escapes the electron gun.

The choice of a beam emission program dictates the design

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of the electron gun modulator. Ideally, one would like to sweep the modulation frequency through the VLF band to determine the strongest propagation frequencies measured at the ground stations. Conversely, increasing the emission time at one frequency increases the probability of obtaining a good measurement at that frequency. It is also desirable to repeat the frequency emission program at various altitudes to determine the effect of altitude of emission on propagation. Varying the angle between the emitted electron beam and the magnetic field (pitch angle) would aid in determining the pitch angle providing the strongest propagation to ground at each frequency. Exploring the effects of the vehicle potential with respect to the background plasma on the VLF propagation is also a useful experiment. However, the short time available during a sounding rocket experiment severely restricts the number of experiments that can be performed, and a compromise must be reached. A series of identical sequences of MEG operations was chosen for the beam program to maximize information gained due to both frequency and altitude variations. Four main MEG pulsing frequencies were chosen in the VLF range at 4.470, 8.970, 14.010, and 17.940 kHz. These frequencies were chosen to cover the range of VLF and to avoid known sources of strong background noise. Pulsing frequencies 180 Hz above and below each main frequency have been included in the program of operations. The MEG will emit pulsing beams of 1 second duration at each frequency. The effects of the release of neutral gas from the beam-emitting payload, for the purpose of minimizing the vehicle potential, will also be explored. With this in mind, the gun operation sequence has been designed as listed in Table 1.

Modulated Electron Gun

Design

The MEG incorporates a modified Pierce design for the gun optics. The cathode was originally intended to be in the shape of a disk but it was found that electron emission only occurred near the edges of the disk, not utilizing the full surface area of the cathode. The cathode was redesigned as a wire that winds back and forth in a serpentine shape (Figure 1) within the envelope of the original disk. This has been shown to maximize the area of electron emission. A focus electrode surrounds the cathode in the plane of the disk and is maintained at the same potential as the cathode. The first (perveance) anode is a hollow modified cylinder in front of the cathode. It is maintained at a positive potential with respect to the cathode and draws the electrons thermionically emitted by the cathode through the hole in the center of the perveance anode. A current in a wire coiled around the

outside of the perveance anode produces a focus magnetic field to minimize the divergence of the electron beam. A second (energy) anode in front of the perveance anode accelerates the emitted electrons to the desired beam energy. A simplified representation of the optics geometry is shown in Figure 2. The vertical portion of the cathode has the serpentine shape, which thermionically emits electrons. The focus electrode ensures that the electric field between the cathode and the anode is not excessively divergent. The perveance anode controls the magnitude of the beam current. The perveance is defined as the beam current divided by the voltage to the power of three halfs ($I/V^{3/2}$). The energy anode determines the energy of the electron beam.

Prototypes of the MEG have been built and tested in the vacuum chamber at SDL. Three of the serpentine cathodes have also been tested in the vacuum chamber. The final design of the electron gun optics section is shown in Figure 3. The cathode is located just below the center of the figure and the electrons are emitted downward. The flight gun optics have been received by SDL and assembly is planned to occur by April 28, 1990. The prototype for the modulator circuit of the MEG has been assembled on a breadboard. A block diagram of the modulator circuit is shown in Figure 4. The diagram includes the arming plug (bottom center), the umbilical connections (top right), the battery packs (bottom right), and the cathode/anode system (to the left of the umbilical connections). The first test of the prototype modulator will use test load resistors. The next test will connect the modulator to the gun optics and the beam current modulation in the vacuum chamber will be performed.

Table 1. Electron Gun Program Sequence.

Time (sec)	Frequency (Hz)	Gas Release
0	4290	on
1	4470	on
2	4650	on
3	gun off	
4	4290	off
5	4470	off
6	4650	off
7	gun off	
8	8790	on
9	8970	on
10	9150	on
11	gun off	
12	8790	off
13	8970	off
14	9150	off
15	gun off	
16	13,830	on
17	14,010	on
18	14,190	on
19	gun off	
20	13,830	off
21	14,010	off
22	14,190	off
23	gun off	
24	17,760	on
25	17,940	on
26	18,120	on
27	gun off	
28	17,760	off
29	17,940	off
30	18,120	off

A Rogowski coil will be used to measure the modulation of the beam current at the required frequencies during the test.

Power System

The energy for the electron gun modules is supplied by individual 3-kV battery power packs for each module. The battery packs consist of Panasonic P-11AA nickel-cadmium 1.2-V, 110-mAH cells. Ten 250-cell modules supply the energy for each electron gun module. Every two cells are connected to a zener diode to protect the module from any cell that becomes discharged during operation. Each 250-cell module incorporates a Kilovac relay to disconnect the module during an overcurrent condition. This is shown in Figure 5, although not all of the cells are shown in the battery pack, as represented by the slash marks. Tests of the batteries under discharge conditions have been performed for some individual cells and a 250-cell module. Figure 6 shows the results of the discharge test of one cell for the third charge-discharge cycle. The data show the cell voltage versus time. No load resistance was applied for the first 10 seconds followed by 10 seconds with the load resistance of 1.3 ohms applied. This was followed by 100 seconds of no load, 280 seconds of the 1.3-ohms resistance, and ending with the load resistance removed. The current drain on the batteries varied with time since $V=I \cdot R$ and the cell voltage decreased with time, but the current provided by the battery cell slowly decreased from a starting value of approximately 1 A. Further tests of individual cells used a 2.5-ohm load resistance to provide for a current close to 0.5 A, since the electron beam would be pulsing with a 50% duty cycle and not operating at 1 A DC. Figure 7 shows the results of a 2.5-ohm test with the resistance switched in and out in the pattern of the actual programmed sequence of operations for nine sequences. There were small differences between individual cells (less than 0.1 V) but the overall pattern of discharge was similar. The averaged results from 5 DC discharges of a 250-cell pack is shown in Figure 8, with an average discharge current of 840 mA. The battery packs will be located in the pressurized section of each gun module.

Waveform Generator

The waveform generator is still in the design stage. A 1-MHz clock will be used as a reference oscillator. The programmable divider will count down the 1-MHz clock to obtain a 7.6294-Hz resolution for beam emission frequency. Various frequencies are obtained by adding multiples of 7.6294 Hz. The controller will determine which multiple of 7.6294 Hz to be output, and this desired clock frequency is sent to the address pointer logic circuit which feeds the frequency into the ROM memory that stores the waveform. The waveform of $e^{1.5kx}$

was selected to produce a sinusoidal current variation for the beam emission. The stored waveform will contain sixteen points which can be used to define the shape of the waveform. The waveform is then fed into a D/A converter that sends a ±1 V analog signal of the waveform at the desired frequency to the beam current modulator. An Altera Maxplus 5128 EPROM will probably be used to perform the programmable divider, address pointer, and ROM memory functions. A decision may be made to move the ROM memory and the D/A converter into the modulator section. This would decrease the number of signals that must pass between the waveform generator and the modulator. It is anticipated to require 1 to 2 weeks to build the waveform generator.

MEG Performance

Computer Model

The Herrmannsfeldt computer model was used to predict the gun performance and to assist in the design. Parametric studies helped to specify an optimum geometry and operating parameters for the electron gun. The results of the computer model showed that the emitted current is proportional to $V^{3/2}$, where V is the potential of the perveance anode with respect to the cathode, and is independent of the potential of the energy anode. The results of the model also show that 1 A is an attainable emission current for the MEG design. Figure 9 shows the results of the code for varying perveance anode potential. The energy anode was at 3 kV for all four panels. The x- and y-axes are in units of distance, while the right y-axis shows the magnetic field strength (provided by the magnetic focus coil) represented by the single curve that starts at the left axis near 200 gauss and ending at the right axis near 30 gauss (only seen in the top panel). The cathode is at the bottom left corner and is the starting point for the horizontal rays representing electron paths. The vertical lines represent equipotentials. The focus electrode is connected to the top of the cathode and slants to the right, bounding the equipotentials on the left. The perveance anode provides the right boundary for the equipotentials and covers a horizontal distance between about 20 and 80 grid units. The energy anode covers the horizontal distance between 100 and 220 grid units and then slants away upward. Only half of the optics geometry is shown and symmetry is assumed about the x-axis. The electron beam rays are seen to begin on the cathode at the left. As the electrons move to the right the beam diverges due to the space charge of the electrons. The magnetic focus field causes a convergence of the beam rays, but as the electrons continue to move to the right the magnetic focus field decreases and the electron beam diverges again. The top panel shows the results for the perveance anode at 3 kV, providing a beam current of 0.97 A. The other

panels, moving downward, used perveance anode potentials of 2 kV, 1 kV, and 1 V, providing beam currents of 0.53 A, 0.19 A, and 0.019 mA, respectively. Since the perveance and energy anode were at different potentials for the lower three panels, equipotential lines exist between them. Figure 10 shows the results of varying the distance between the cathode and the focus electrode as the geometry of the optics were refined. The equipotential lines are not shown for clarity. Both perveance and energy anode were at 3 kV. The top panel had the cathode and the focus electrode aligned, providing a beam current of 1.2 A. The next three panels below the top panel show the results of moving the cathode back (to the left of the focus electrode) with the effect of decreasing the beam current to 1.0, 0.87, and 0.55 A. The bottom panel shows the results of moving the cathode forward of the focus electrode. Although the beam current is large (1.2 A), a large current is intercepted by the perveance anode, which is an unacceptable result. Figure 11 shows the results of providing a gap between the cathode and the focus electrode, which is a physically more realistic model. However the results did not change significantly and the computer code run-time increased greatly and so was not used for the parametric studies. The conclusions drawn from the results of the model were that the 1-A beam current was attainable. The minimum magnetic field for the flow confinement coil was found to be 200 gauss with an optimum value near 400 gauss. The distance between the filament and the focus electrode is a very critical parameter in determining the gun efficiency.

Vacuum Chamber Performance

The MEG was operated in a vacuum chamber to characterize its performance. The filament temperature was varied in order to choose an optimum operating value. Figure 12 shows the results from the vacuum chamber test. The top panel shows the beam current as a function of filament temperature for various perveance and energy anode potentials from 500 to 3000 V. The filament temperature is measured photometrically and hence a brightness must be converted to actual temperature. A filament temperature of about 2700° C (2400° C-Brightness) ensures that the filament is near saturation. Operation of the filament near this temperature prevents the beam emission current from being very sensitive to variations in the filament temperature, as seen in the figure. The bottom panel shows the beam current as a function of the perveance and energy anode potential for the operational filament temperature. The theoretical curve of an ideal electron gun with a perveance of 6.46 microperv is in good agreement with the performance of the electron gun. The electron gun filament is made from pure tungsten with 3% rhenium. The rhenium decreases the brittleness of the filament. The melting point of tungsten is 3370° C, while the melting point

of rhenium is 3167° C. The rhenium on the surface of the filament is vaporized and does not contribute to the operating characteristics of the filament. The rhenium not on the surface is trapped by the lattice structure of the tungsten and cannot escape, increasing the strength of the filament.

The perveance anode was originally constructed from oxygen-free copper to take advantage of the large thermal conductivity of copper. However, the low melting point of copper (1083° C) proved to be a problem. It was found during the vacuum chamber tests that a small error in the distance between the cathode and the focus electrode drastically changed the efficiency of the gun. As a result an appreciable current was intercepted by the perveance anode which partially melted, streaming material into the cathode. Because of this the perveance anode has been changed to molybdenum which has a higher melting point of 2620° C. The higher melting temperature has been achieved at the expense of the higher thermal conductivity of copper. The energy anode is still made of copper.

Filament Lifetime

Three filaments were tested to failure in the vacuum chamber. The lifetime of the cathodes was observed to be between about 30 minutes and 2 hours, however the shortest lifetime was due to the bombardment of one of the cathodes with material from the partially melted perveance anode as mentioned above. The lifetime of the filaments is thought to be shortened by the location of the magnetic focus coil inside the vacuum portion of the electron gun optics, coupled with the small path available for outgassing of the air from the coil. The slow outgassing of the focus coil provided an increased pressure near the cathode, drastically reducing the cathode lifetime. This problem has been addressed by locating the focus coil in the pressurized section of the redesigned flight MEG. Evaporation of the filament is thought not to be a problem since the operating temperature is well below the melting point of tungsten. Ion bombardment is also thought not to be a problem unless the bombardment greatly increases the surface temperature of the cathode. All three cathodes failed at the same place, the midway point of the filament. This strengthens the argument against ion bombardment as a factor determining the filament lifetime since the ions would impact the filament at random locations causing failure of the filament at random locations. Thus chemical reaction of the filament at its operating temperature with neutral gas is the most likely cause for filament failure. The chemical reaction would increase the resistance of the filament, greatly increasing the filament temperature, causing filament failure.

Overcurrent Protection

The electron gun is protected from a catastrophic failure due to overcurrent by a delay circuit. During an overcurrent condition a relay in the modulator circuit opens the Kilovac relays in each 250-cell battery pack (K81C in the lower right of Figure 4), disconnecting the batteries from the electron gun. In addition, the final high voltage relay (KC-22, just above the battery packs in the lower right of Figure 4) is also switched open. A delay circuit (to the left of the battery packs in Figure 4) would then close the relays after a programmed amount of time. The value of the overcurrent limit has not been determined yet. The electron guns are programmed to operate at 1 A and the batteries can supply 10 A during a short circuit, so a reasonable value to set as a limit would be 2-3 A. The amount of delay time before reconnecting the batteries has also not been determined yet. The CHARGE-2 mission used a 0.5-second delay for gun operation recovery to allow dissipation of any plasma surrounding the filament produced by an overcurrent.

Flight Configuration

MEG Modules

The MEG module has been designed as a 3-kV, 1-A electron gun consisting of the modulator, battery power supply, and gun optics. The waveform generator is located in the science section. The modules are isolated from the science instruments. Each module is enclosed in its own pressurized section. The modular design allows multiple MEGs to be stacked to achieve beam currents larger than 1 A. This also increases reliability since a failure of one module will not affect any other module. Each module is 24 inches in length and weighs 141 lbs. The CHARGE-2B experiment will utilize three MEG modules to produce a total beam current of 3 A. The beam is injected radially outward from the rocket cylinder.

Controller

The controller has been designed to utilize a 360° absolute rotary optical encoder, possibly the Compumotor EP Absolute Rotary Encoder, driven by a 400-Hz Globe TRW motor. An optical encoder was chosen because it is mechanically driven, which reduces the possibility of a failure due to transient upsets. The motor driver will be connected to the Wallops Flight Facility timer and will have a line in from the umbilical to position it prior to launch. The optical encoder will send 16 bits of digital data to an electronic decoder which issues commands to the MEGs and other instruments. The controller is located in the science section.

Beam Current Monitor

A Rogowski coil will be mounted at the exit port of each MEG to measure the current that escapes the gun. The output from the Rogowski coils will be fed into peak sample-and-hold circuits. Both positive and negative peaks of the beam current will be captured within a given 400-microsecond window and the conditioned signal will be routed to the telemetry system. The peak detectors will be reset before capturing the peaks from the next 400-microsecond window. Thus the beam current data will be sampled at 2,500 Hz. Since the telemetry rate for these channels is 5,000 Hz, the update rate of 2,500 Hz is at the Nyquist frequency, minimizing aliasing of the output signal. An additional filter to prevent aliasing of frequencies above 2,500 Hz is incorporated into the beam current monitor. An internal calibration source will produce a series of known values to ensure that the beam current monitor system is functioning properly prior to launch. The electronics for the beam current monitor are located in the science section.

Tether Voltage Monitor

The emission of electrons from the mother vehicle will cause the mother to attain a positive potential with respect to the background plasma. The vehicle potential will alter the energy of the escaping beam electrons. The energy of the electron beam is an important parameter in determining the propagation characteristics of the VLF waves produced, hence the vehicle potential is an important quantity to measure. The mother potential with respect to the plasma will be measured by deploying a daughter payload connected to the mother by a conducting, insulated tether. The daughter will be deployed to a distance of up to 426 m and will serve as an electrical reference to the mother. The source for driving the mother potential will be the pulsing electron beam, hence the mother potential may change at rates comparable to the beam pulsing rate. Therefore a peak sample-and-hold circuit identical to that used for the beam current monitor will be used to measure the changing mother potential. Four different ranges of mother potential will be measured simultaneously at ±100 V, ±1000 V, ±2000 V, and ±4000 V. An internal calibration source will produce a series of known values to ensure that the tether voltage monitor system is functioning properly prior to launch. The tether voltage monitor is located in the science section.

Schedule

The schedule calls for completion of fabrication and testing of the payload in July, 1990. Delivery of the payload to Wallops Flight Facility is scheduled for August, 1990. The

vacuum chamber test of the payload is scheduled for the end of August, 1990. The payload would then be delivered to Poker Flats Research Range, Alaska, in September, 1990. The earliest launch date is currently scheduled for the end of September, 1990. Problems that have developed in manufacturing the sections for the MEG modules may prevent a launch before early 1991.

Figure Captions

Figure 1. Representation of the serpentine shape of the cathode.

Figure 2. Simplified representation of the electron gun optics.

Figure 3. Drawing of the actual MEG assembly.

Figure 4. Block diagram of the MEG modulator.

Figure 5. Configuration of the 250-cell battery packs.

Figure 6. Performance of a single battery cell at a current close to 1 A.

Figure 7. Performance of a single battery cell at a current close to 0.5 A for repeating sequences.

Figure 8. Average of five tests of the 250-cell battery packs at an average current of 0.84 A.

Figure 9. Herrmannsfeldt computer model of the electron gun optics with varying perveance anode potential.

Figure 10. Herrmannsfeldt computer model of the electron gun optics with varying cathode-to-focus electrode distance.

Figure 11. Herrmannsfeldt computer model of the electron gun optics including the separation between the cathode and the focus electrode.

Figure 12. Performance of the electron gun in the vacuum chamber.

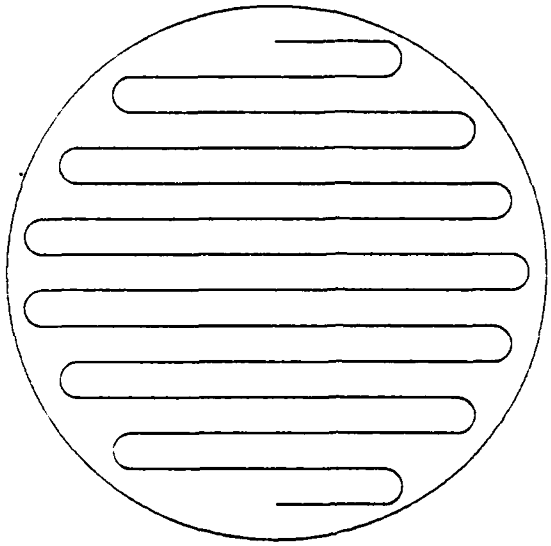


Figure 1.

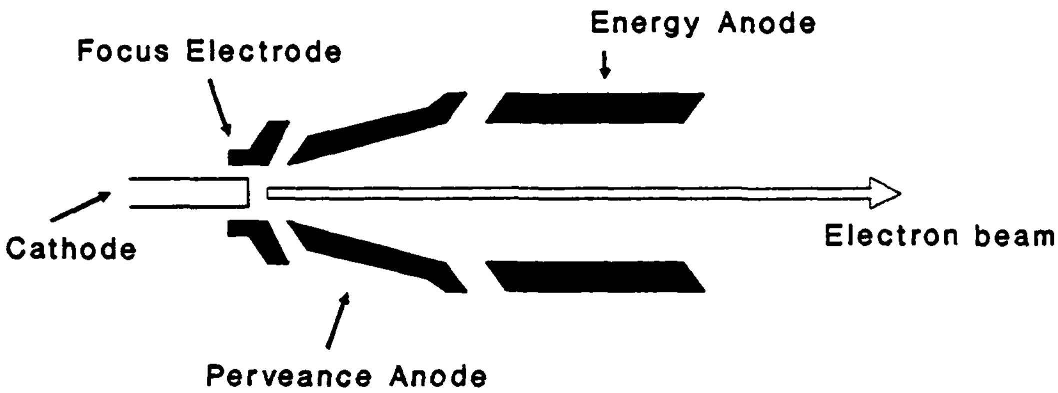

Energy Anode
Focus Electrode
Cathode
Electron beam
Perveance Anode

Figure 2.

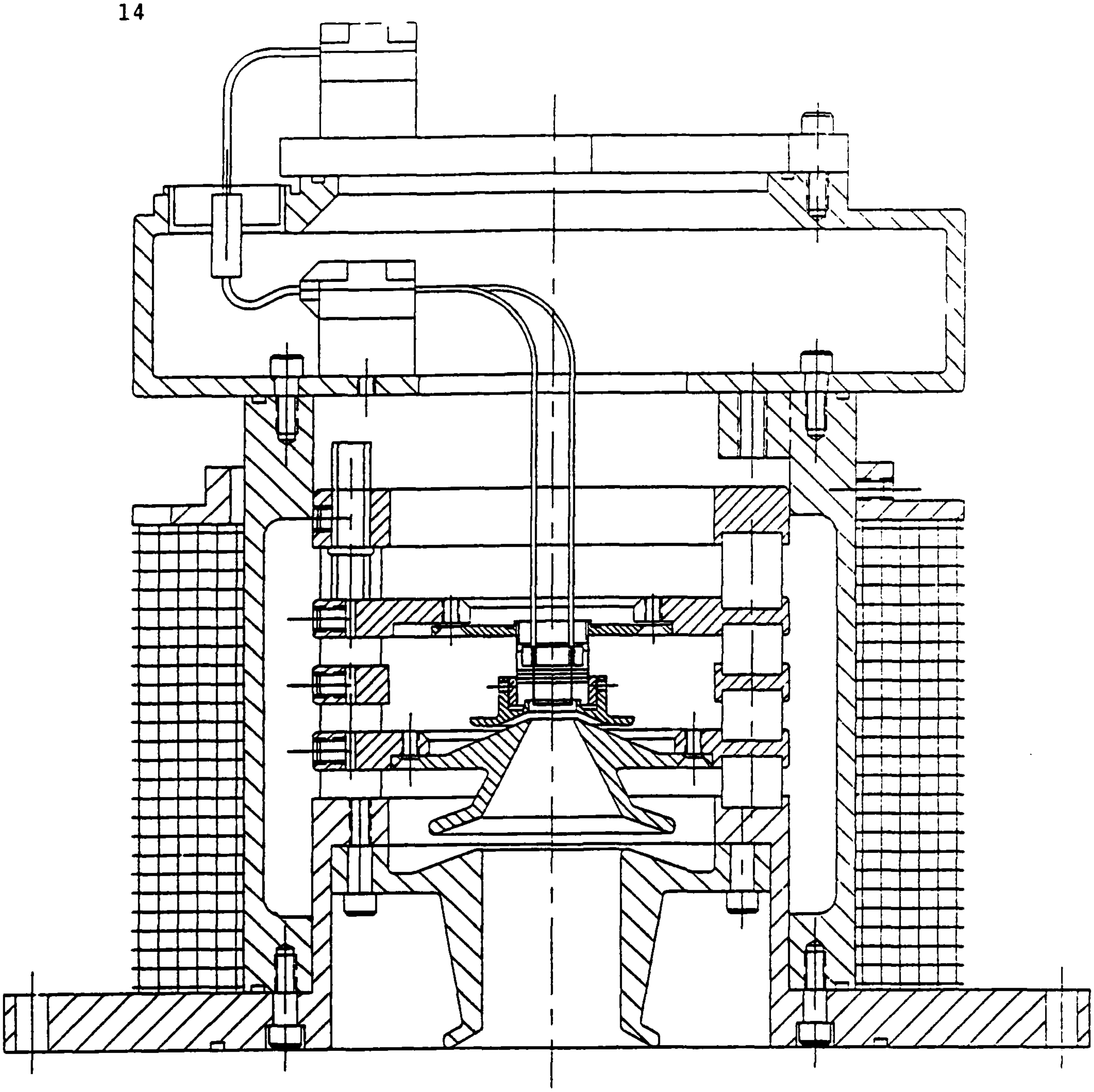


Figure 3.

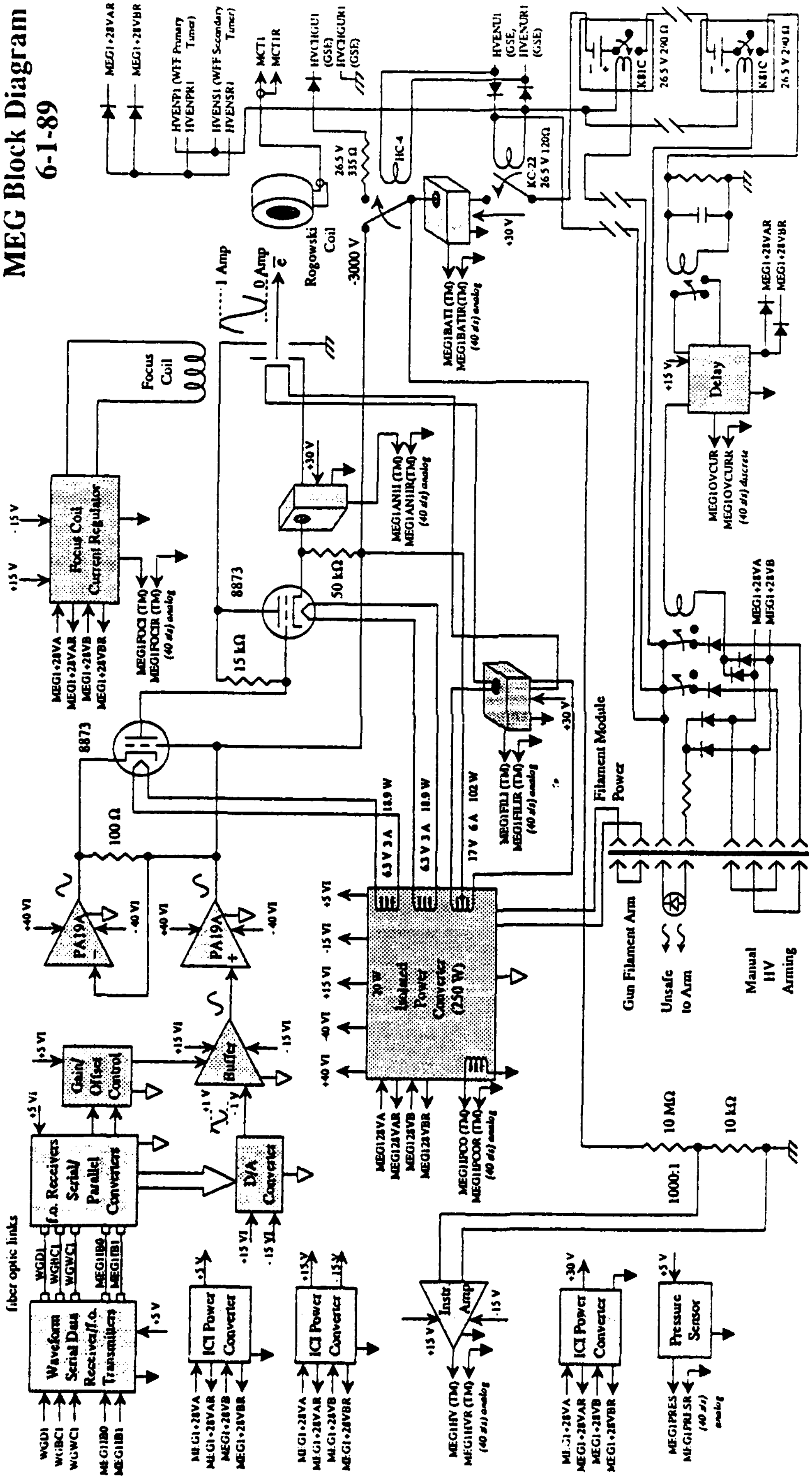

MEG Block Diagram
6-1-89
Focus Coil
Focus Coil Current Regulator
Rogowski Coil
-3000 V
1 Amp
0 Amp
8873
15 kΩ
50 kΩ
100 Ω
PA19A
Buffer
Gain/ Offset Control
D/A Converter
f.o. Receivers Serial/ Parallel Converters
fiber optic links
Waveform Serial Data Receiver/f.o. Transmitters
30 W Isolated Power Converter (250 W)
6.3 V 3 A 18.9 W
17 V 6 A 102 W
Filament Module Power
Gun Filament Arm
Unsafe to Arm
Manual HV Arming
Delay
10 MΩ
10 kΩ
1000:1
Instr Amp
ICI Power Converter
Pressure Sensor
HC-4
KC-22
K81C
26.5 V 290 Ω

Figure 4.

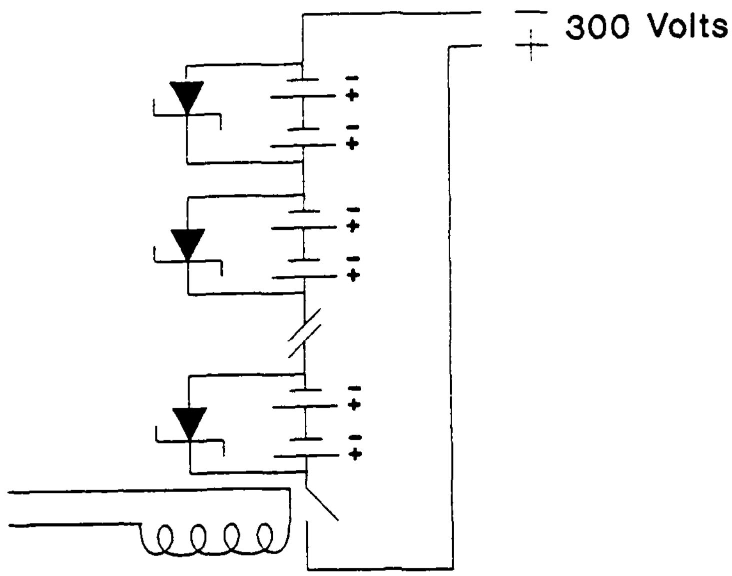


Figure 5.

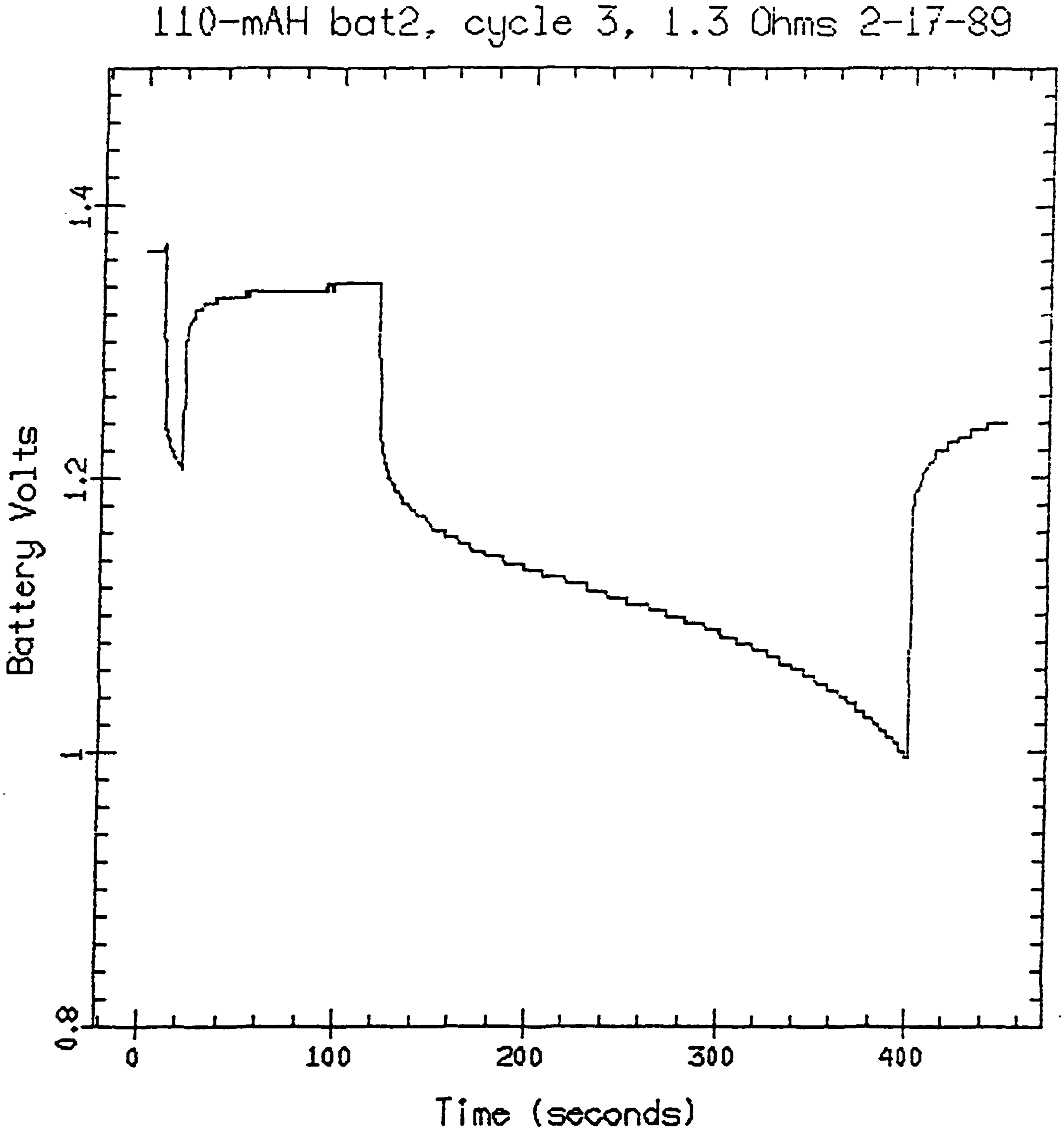

110-mAH bat2, cycle 3, 1.3 Ohms 2-17-89
Battery Volts
1.4
1.2
1
0.8
0
100
200
300
400
Time (seconds)

Figure 6.

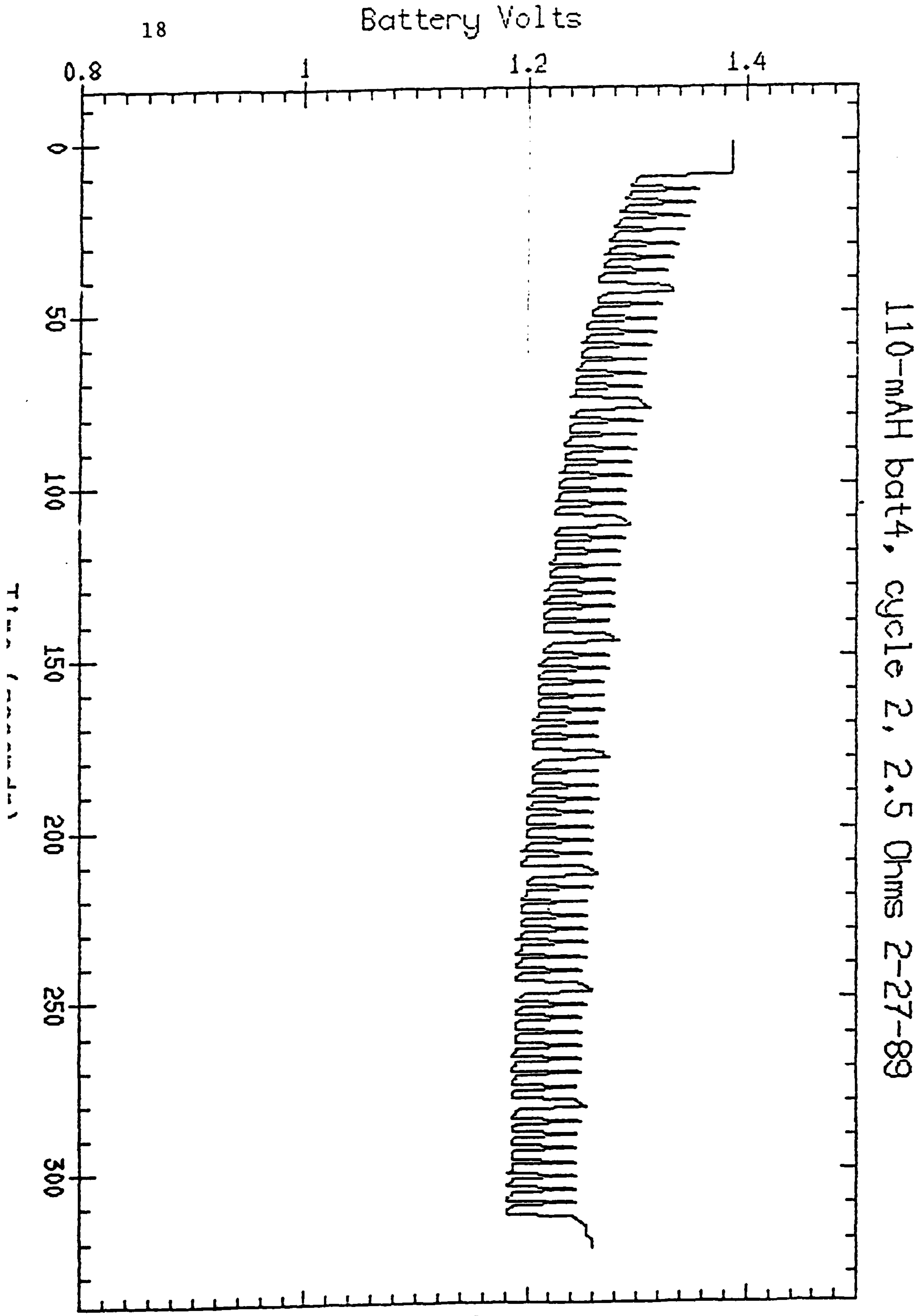
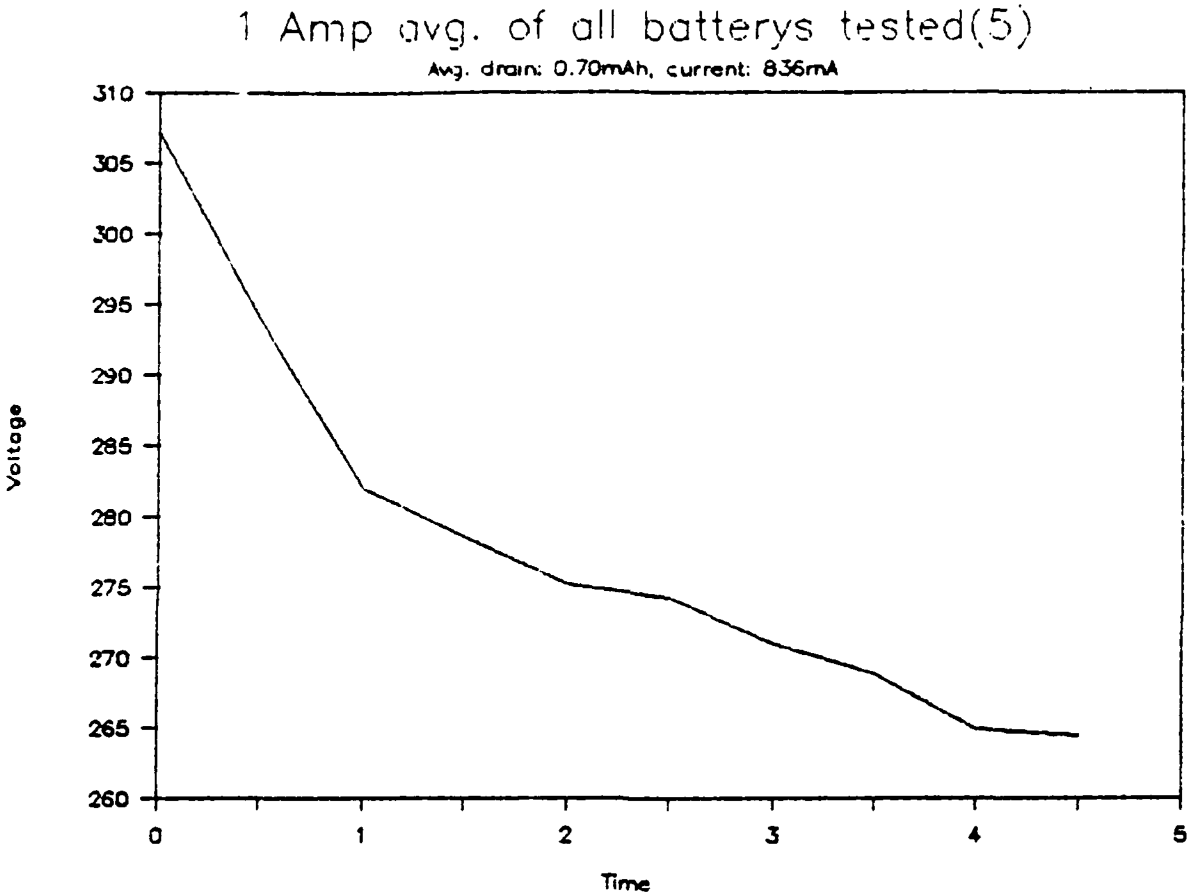
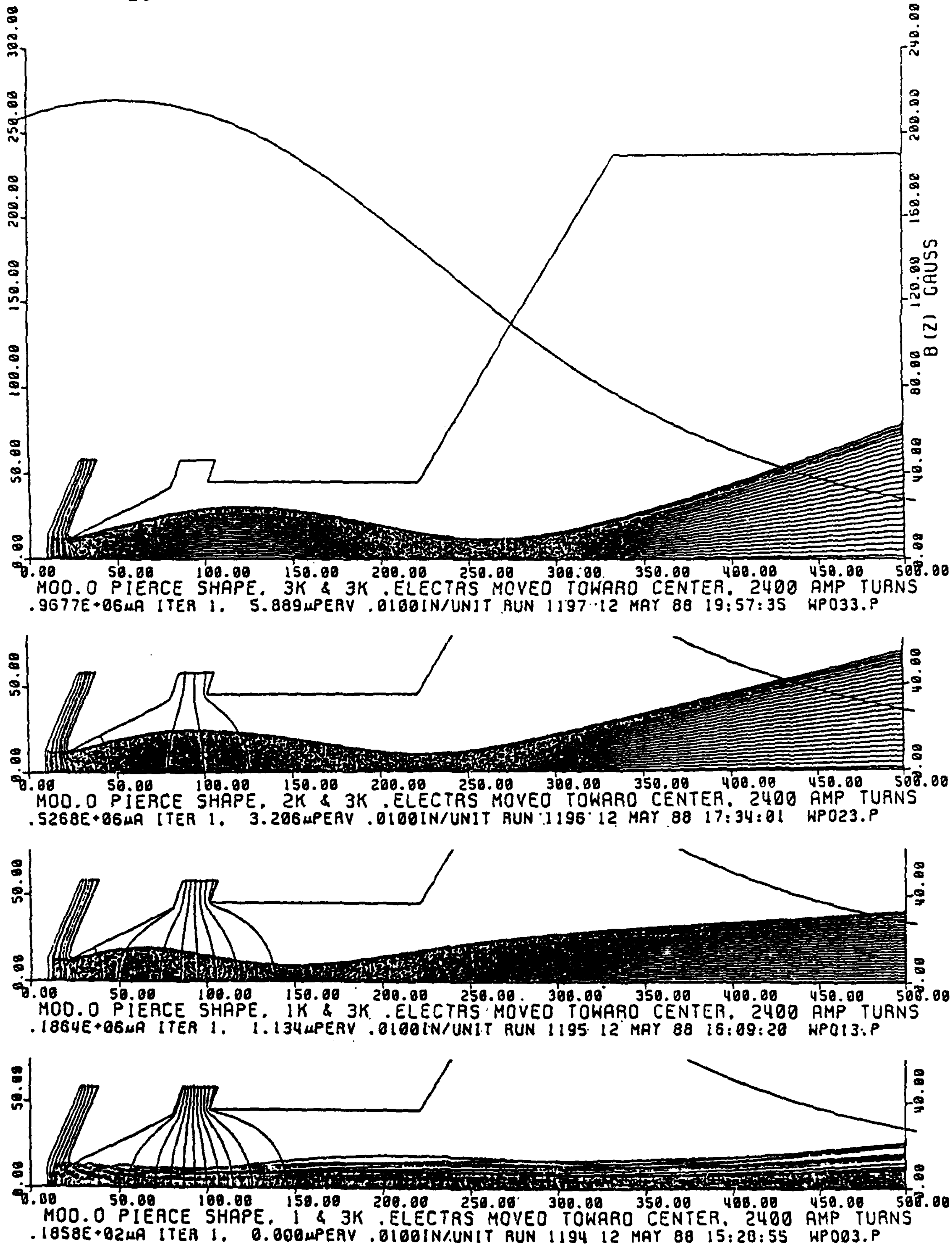

Battery Volts
0.8
1
1.2
1.4
0
50
100
150
200
250
300
110-mAH bat4, cycle 2, 2.5 Ohms 2-27-89

Figure 7.



1 Amp avg. of all batterys tested(5)
Avg. drain: 0.70mAh, current: 836mA
Voltage
310
305
300
295
290
285
280
275
270
265
260
0
1
2
3
4
5
Time

Figure 8.



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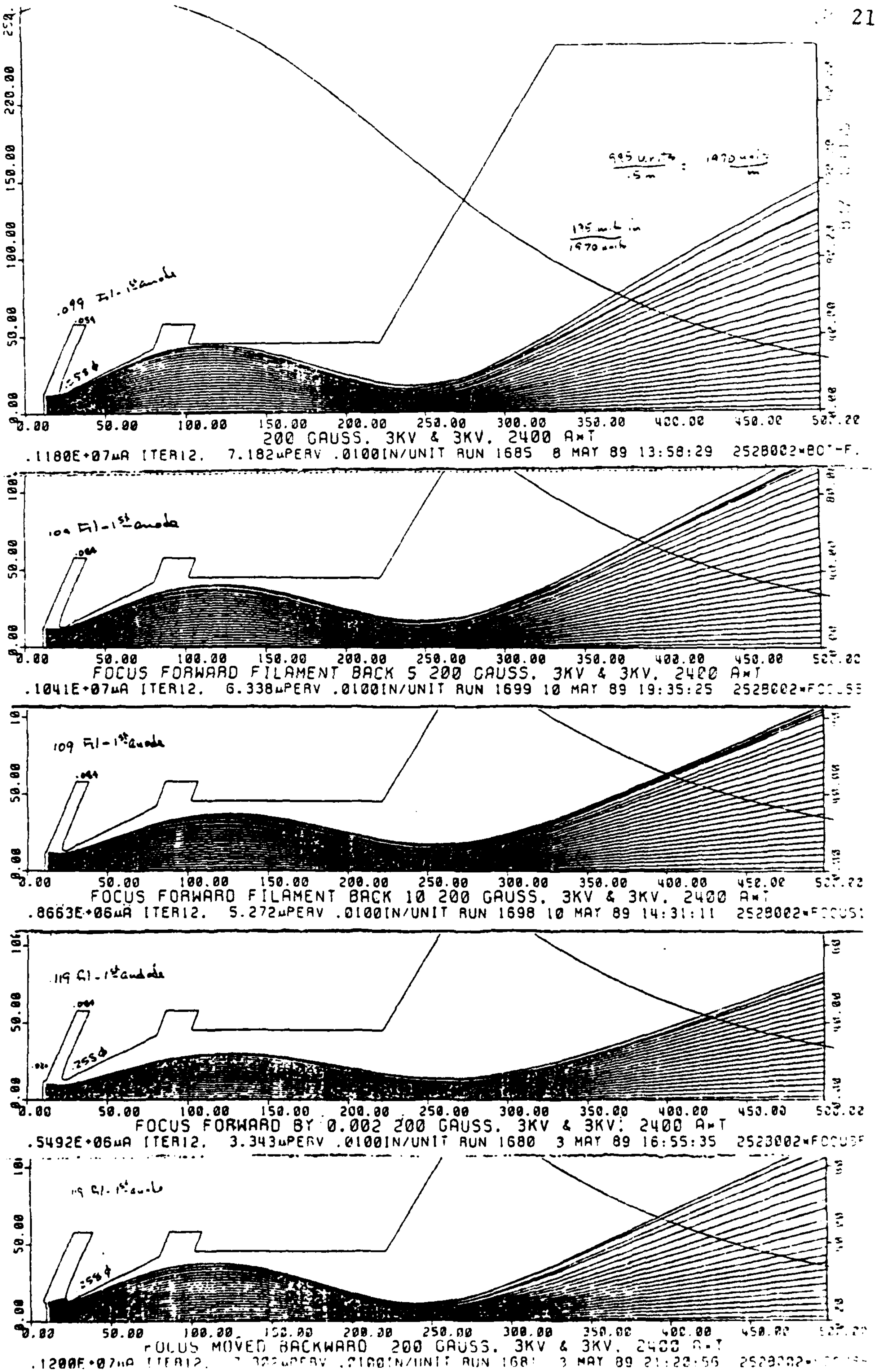
.1858E+02μA ITER 1, 0.000μPERV .0100IN/UNIT RUN 1194 12 MAY 88 15:20:55 WP003.P

Figure 9.



200 GAUSS. 3KV & 3KV. 2400 A*T
.1180E+07uA ITER12. 7.182uPERV .0100IN/UNIT RUN 1685 8 MAY 89 13:58:29
.099 Fil-1st anode
FOCUS FORWARD FILAMENT BACK 5 200 GAUSS. 3KV & 3KV. 2400 A*T
.1041E+07uA ITER12. 6.338uPERV .0100IN/UNIT RUN 1699 10 MAY 89 19:35:25
.104 Fil-1st anode
FOCUS FORWARD FILAMENT BACK 10 200 GAUSS. 3KV & 3KV. 2400 A*T
.8663E+06uA ITER12. 5.272uPERV .0100IN/UNIT RUN 1698 10 MAY 89 14:31:11
109 Fil-1st anode
FOCUS FORWARD BY 0.002 200 GAUSS. 3KV & 3KV. 2400 A*T
.5492E+06uA ITER12. 3.343uPERV .0100IN/UNIT RUN 1680 3 MAY 89 16:55:35
.119 Fil-1st anode
FOCUS MOVED BACKWARD 200 GAUSS. 3KV & 3KV. 2400 A*T
.1200E+07uA ITER12.

Figure 10.

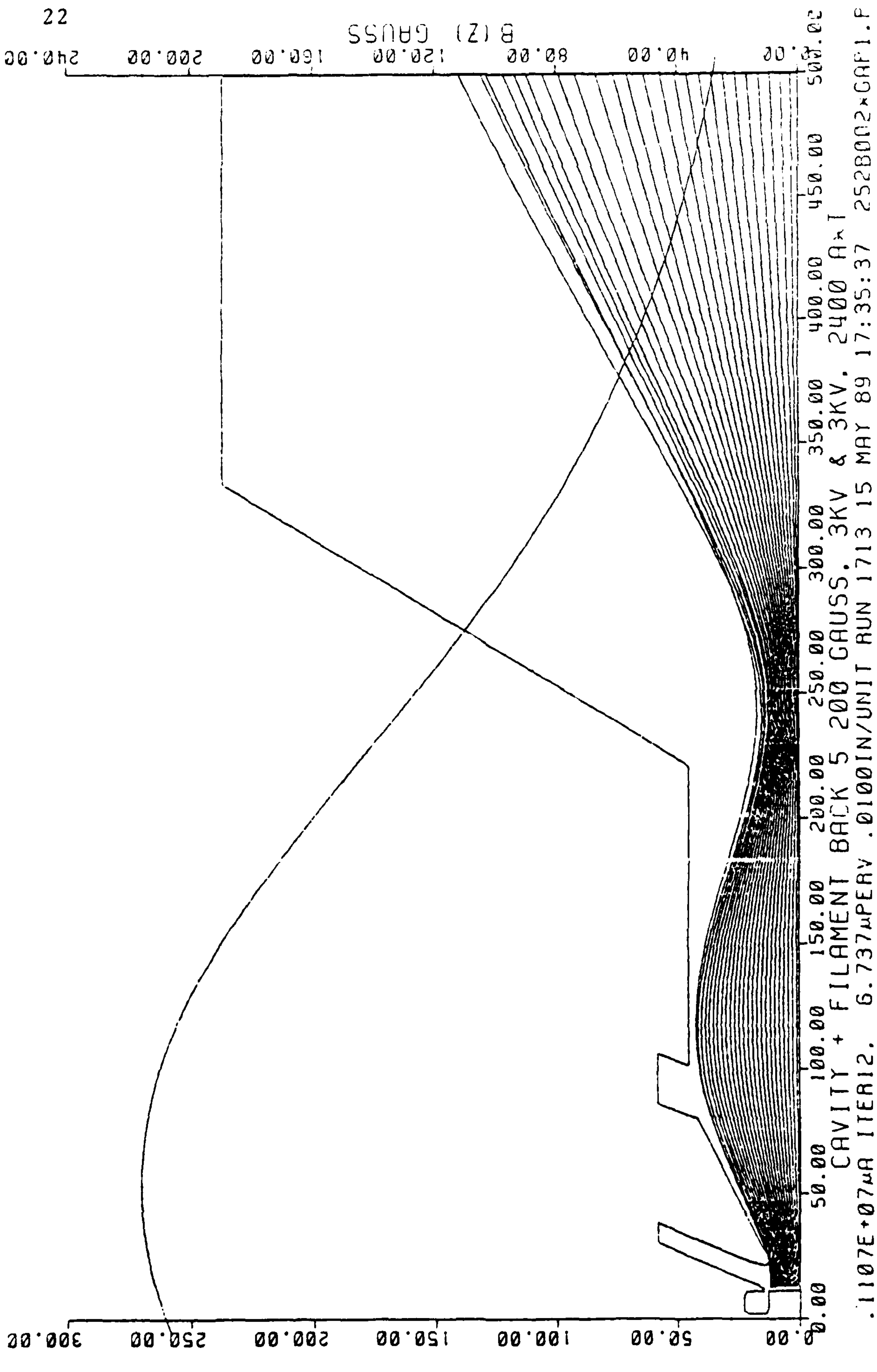
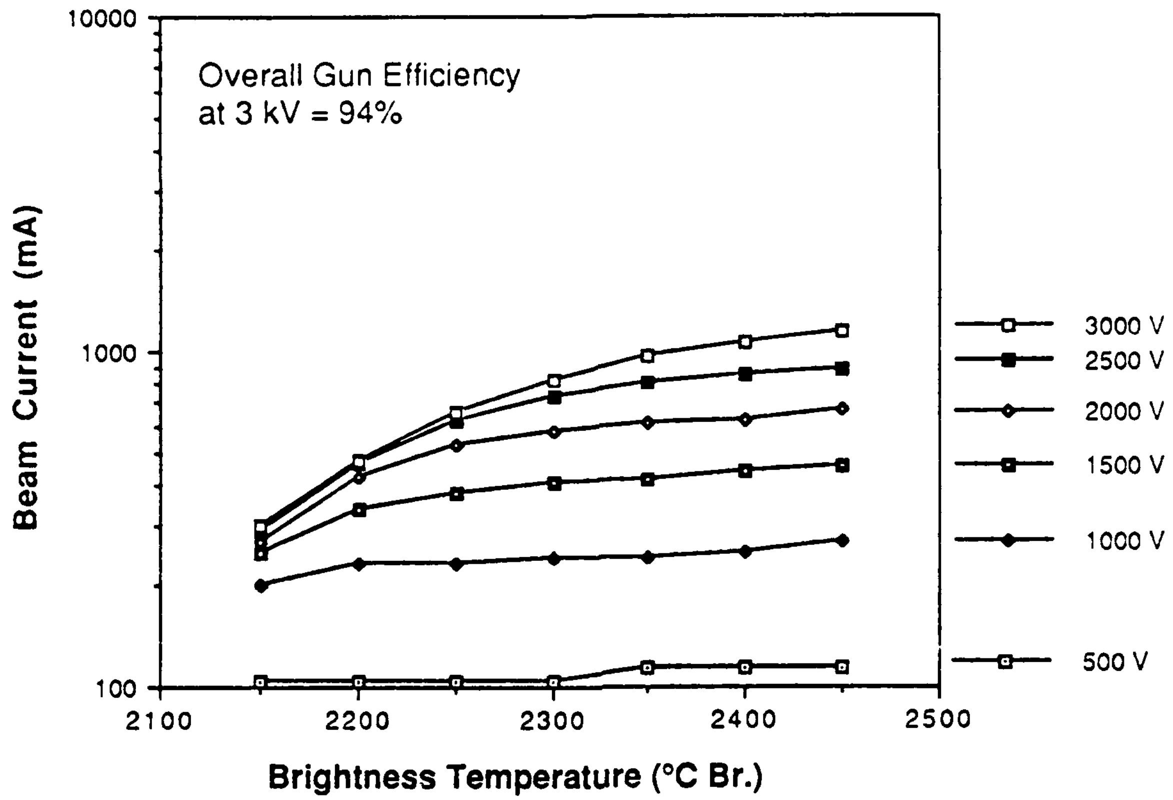

B(Z) GAUSS
0.00
40.00
80.00
120.00
160.00
200.00
240.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
CAVITY + FILAMENT BACK 5 200 GAUSS. 3KV & 3KV. 2400 A*T
.1107E+07μA ITER12. 6.737μPERV .0100IN/UNIT RUN 1713 15 MAY 89 17:35:37 252B002*GAF1.F

Figure 11.

CHARGE-2B Electron Gun Vacuum Test
Data from May 10, 1989



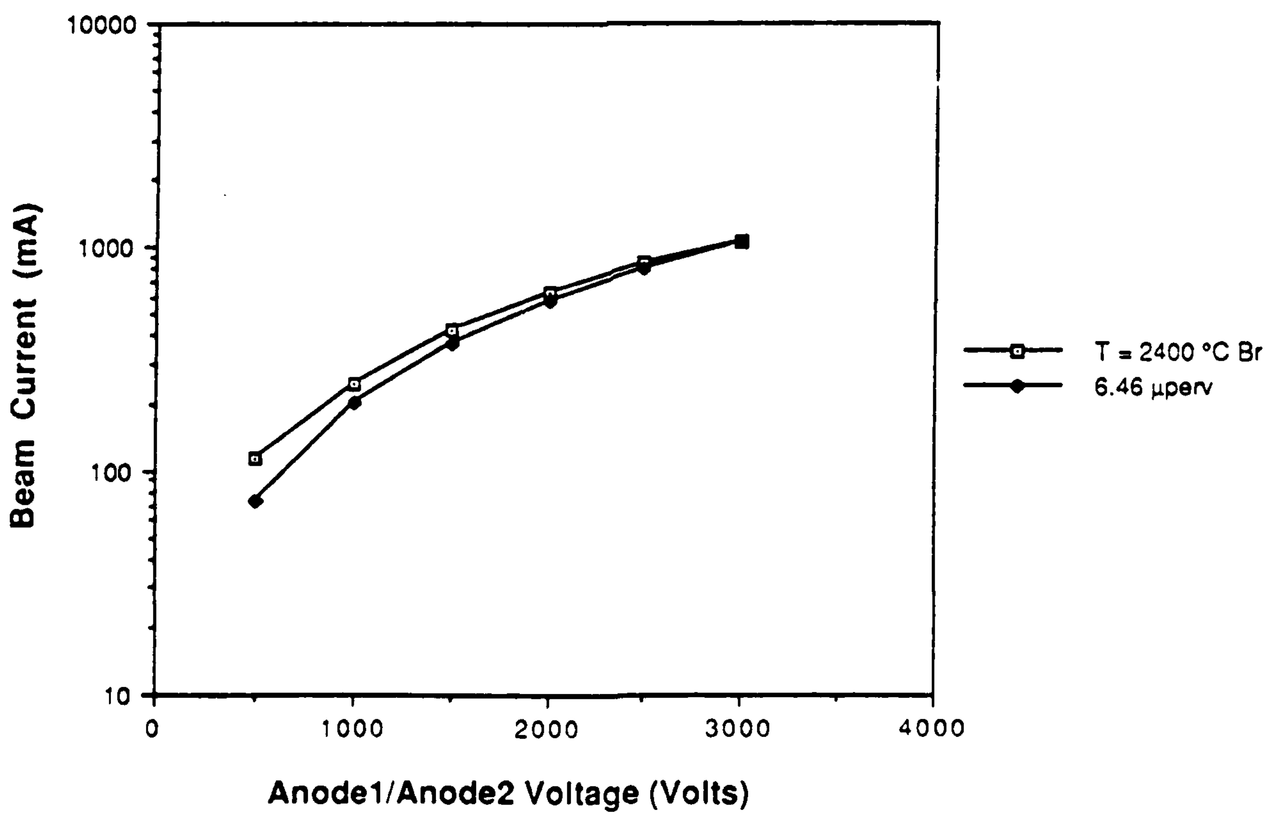


Figure 12.